ENSO Influences on Atmospheric Circulation and Precipitation in the Western United States

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Abstract: The influence of ENSO on atmospheric circulation and precipitation over the western United States is presented from two perspectives. First, ENSO-associated circulation patterns over the North Pacific/North America sector were identified using an REOF *(rotated empirical orthogonal function)* analysis of the 700-mb height field and compositing these for extreme phases of the Southern Oscillation Index. Five patterns were identified with associations to extremes of the SOI, similar to results from previous investigations. To determine the precipitation response, composites of precipitation anomalies were taken over cool season months (November through March) using circulation patterns that project onto these REOFs with strongly positive and strongly negative amplitudes. Several of these have strong precipitation expressions over the western United States. Second, we examine the variability of precipitation during the warm and cool phases of ENSO for different locations in the western United States. Choosing sites in the Pacific Northwest and Desert Southwest regions, we diagnose the ENSO response by considering four subsets of the pattern of precipitation and associated atmospheric circulation. The four subsets include wetter- and drier-than-normal months during the warm and the cool ENSO phases. While the Southwest tends toward higher precipitation during the warm phase and lower precipitation during the cool phase, it has both wet and dry months during each phase; analogously, the Northwest tends to be dry during the warm phase and wet during the cool phase but also contains wet and dry months during each phase. Interestingly, circulation patterns and the spatial distribution of precipitation during *a)* the wet cases of the two phases and *b)* the dry cases of the two phases, for each of the two regions, are distinct enough to suggest systematic differences in the winter storm regimes (not just the storm frequency but also the storm pattern) for the two ENSO phases.

Introduction

One of the few secure predictive links to seasonal anomalous precipitation in the western United States appears to involve the relationship with large-scale disturbed conditions in the tropical Pacific, known as the El Niño/Southern Oscillation phenomenon. In the present study, both the warm and cool phases of the El Niño/Southern Oscillation are considered and are referred to collectively as *ENSO* (*eg*, Barnett *et al* 1991).

Concerning the linkage between ENSO and the western United States, several previous studies have considered precipitation (Ropelewski and Halpert 1986; Schoner and Nicholsen 1989; Andrade and Sellers 1988; Redmond and Koch 1991; Epstein 1992; Redmond and Cayan 1994) and also streamflow and snowpack (Webb and Betancourt 1992; Cayan and Peterson 1989; Redmond and Koch 1991; Cayan and Webb 1991; Kahya and Dracup 1993). Compared to relationships with precipitation in the tropical Pacific (Ropelewski and Halpert 1987), those in North America are relatively weak, and the ones that emerge for the Desert Southwest and Pacific Northwest are unreliable enough that Ropelewski and Halpert (1986) did not include them in their set of ENSO-related study regions across the United States.

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A different methodology reveals, however, that there are statistically significant impacts on the frequency and amount of precipitation during ENSO extremes (both negative and positive phases of the Southern Oscillation Index). This linkage has been detected in precipitation records at stations in each of the two regions (Redmond and Koch 1991; Epstein 1992; Cayan and Webb 1992; Redmond and Cayan 1994).

Some of the pertinent results from previous studies are summarized as follows. Both phases of ENSO exhibit significant anomalous associations with regional precipitation over the western United States. The strongest associations (correlations between SOI and streamflow and between SOI and snowpack) are with precipitation in the Northwest (from Washington to western Montana) and in the Southwest (from southeastern California to New Mexico). The Northwest tends to be dry and the Southwest tends to be wet during the Northern Hemisphere winter of the ENSO mature warm phase. The opposite conditions occur during Northern Hemisphere winters of the ENSO mature cool phase. Similar responses are noted for individual months from about October through May. There also appears to be a several-month lag, such that the SOI leads the circulation and precipitation. The SOI in summer/fall is a reliable precursor to tropical atmospheric behavior during the following winter. In turn, the summer/fall SOI is also related (although not as strongly) to winter extratropical Pacific climate including precipitation in the regions noted above (Redmond and Cayan 1994).

The present study builds on the previous body of results by scrutinizing the links to various atmospheric circulation patterns and by focusing on monthly, as opposed to seasonal, variations. Both negative and positive phases of the SOI are considered in relating ENSO to monthly atmospheric circulation over the North Pacific and western North America sector and to the pattern of regional precipitation over the western United States.

Data

Monthly total precipitation was used from 94 climate divisions over the western conterminous United States west of 102°W. Precipitation values are averages over several stations within a climate division, as defined by the National Climate Data Center (Karl and Knight 1985). The divisional data series employed covers 1895 through 1991. Since divisonal data were not reported before 1931, they were retrospectively estimated by NCDC from statewide average values of nearby states using a multiple regression scheme (Karl and Knight 1985). Specific regions were constructed by averaging the anomalies of monthly precipitation over 11 divisions in the Pacific Northwest *(PNW)* and 10 divisions in the desert Southwest *(DSW)*. A third region, the northern Rocky Mountains, was also examined, but associated circulation and precipitation patterns were similar to those for PNW, so they are not shown here. These regions are shown in Figure 1, and associated circulation and precipitation patterns are delineated later in this paper, under "Extreme Precipitation During Warm and Cool Phases of ENSO". Precipitation considered in this study is for November through March (NDJFM), when the ENSO influence on climate fluctuations over the western United States is likely to be strongest (Redmond and Cayan 1994).

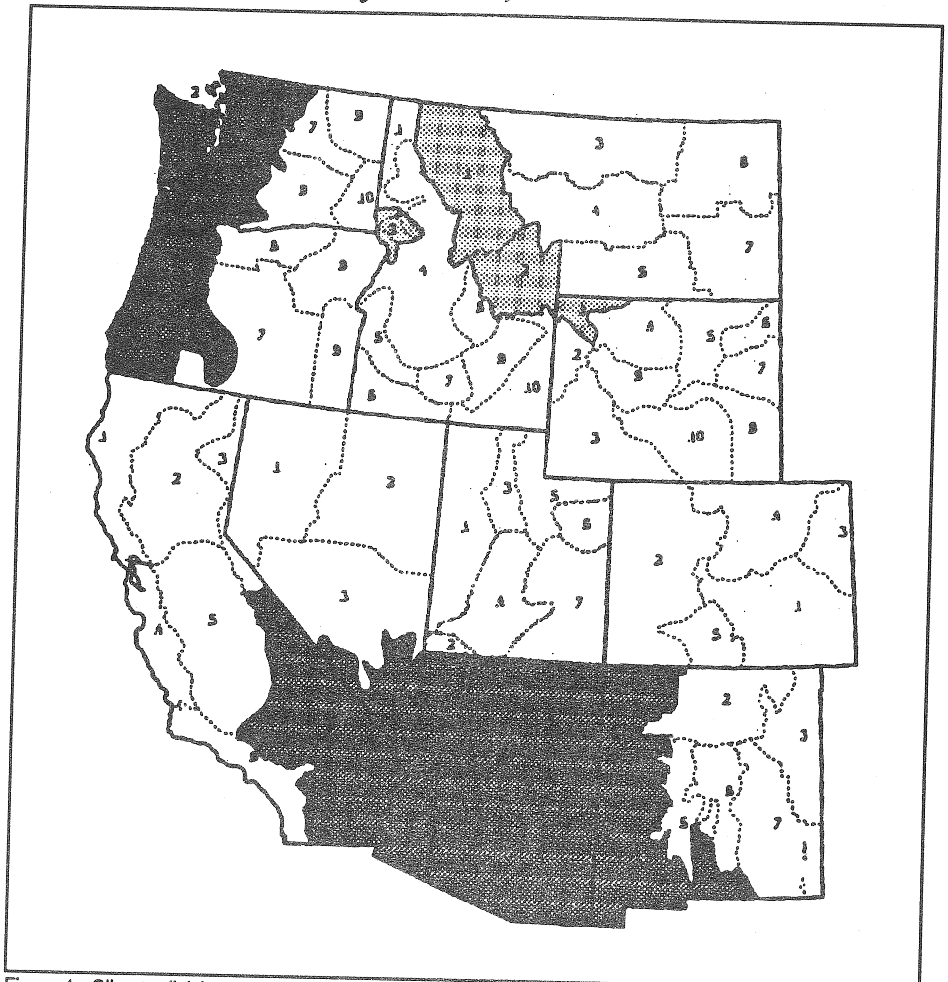

Figure 1. Climate divisions employed in the Pacific Northwest and Desert Southwest regions used in the regional precipitation analyses. The northern Rocky Mountain region in Idaho, Montana, and Wyoming was also considered, but results are not shown here.

Atmospheric circulation measures are obtained from monthly 700-mb height on a 5° latitude by 10° longitude Northern Hemisphere staggered grid, provided by the NOAA Climate Analysis Center. The 700-mb height data are for the NDJFM cool season from 1947-48 through 1990-91.

The Southern Oscillation Index, a normalized difference in monthly anomalies of surface pressure between Tahiti and Darwin (Ropelewski and Jones 1987), was employed for 1895 through 1991. The June-November average of the monthly values, denoted *JJASON*, was constructed as an index of the summer/fall SOI. To investigate linkages to the tropical Pacific, the JJASON SOI index was related to the atmospheric circulation and precipitation anomalies over the western United States. In all cases, the analyses compare JJASON SOI and the overlapping/subsequent fall-spring NDJFM monthly atmospheric circulation and precipitation. When the SOI is negative, the tropical Pacific is usually in its warm state; when the SOI is positive, the tropical Pacific is usually in its cool state. In this study, a negative JJASON average normalized SOI anomaly ≤–0.5 is used to designate the warm phase of ENSO, called *El Niño*, and a positive SOI ≥+0.5 designates the cool phase, called *La Niña*.

700-mb Height REOFs: Their Relationship to the SOI and Precipitation

Our first approach was to isolate atmospheric circulation patterns associated with ENSO and then to determine how each of these affected precipitation over the western United States. The atmospheric circulation patterns were determined using an REOF *(rotated empirical orthogonal function)* analysis (Barnston and Livezey 1987) of the monthly 700-mb height anomaly field. The NDJFM cool season months were employed to investigate the winter-like response. The anomaly fields were constructed by removing the individual monthly long-term means (1947-1972 base period). All five months were pooled together. Since the focus is on the western United States, we only considered the sector of the 700-mb height from 110°E to 65°W longitude and from 20°N to 70°N latitude. Given the REOFs, their relationship to the two phases of the SOI and their relationship to the geographic distribution of precipitation over the western United States were investigated.

700-mb Height REOFs: Their Relationship to the SOI

A traditional empirical orthogonal function analysis (Davis 1976) was employed to isolate a limited number of spatial modes (spatially uncorrelated), along with their associated time-varying coefficients (temporally uncorrelated). The monthly 700-mb height anomaly data analyzed were multiplied by $[\cos(\text{latitude})]^{0.5}$ to provide equal weighting of the variance over each grid in the domain. The first eight EOFs, ordered by variance, were retained and rotated using the IMSL library "varimax" rotation. This rotation preserves temporal orthogonality, but the resulting spatial patterns are no longer constrained to be uncorrelated. The resulting REOFs still contain the same amount of variance (in this case the sum of the variance is 73%), but the variance is more evenly distributed over the eight REOFs than it was for the original EOF analysis, whose variance is dominated by the first few components (Table 1).

Table 1
REOFs VARIANCE EXPLAINED, NDJFM, 1947-48 through 1980-81

	1 WPO	2 PNA1	3 PNA2	4	5 EP	6 TNH	7	8
Explained Variance (%)	14.8	11.4	11.4	8.0	7.8	6.8	6.8	5.6

The REOF patterns were then evaluated for ENSO influences, as gaged by their correspondence with the SOI. First, strong positive and negative REOF cases were identified, based on the amplitude of the time coefficients of the REOFs. A threshold was chosen such that each case contained between 30 and 44 months; together the positive and negative extremes of each REOF represent about one-third of the 225 total over the data set. This threshold, amplitudes ≥ 1, is at a level of one standard deviation of each of the REOF time series. Hereafter, the extreme cases selected under this criterion are called "strong positive" and "strong negative" extremes of the REOFs.

Table 2 is a set of contingencies, providing the number of months with strong positive or negative expressions of each of the eight REOFs for El Niño, La Niña, and for all conditions regardless of ENSO state.

Another measure is in Table 3, which gives the average value of each of the REOF amplitudes during the NDJFM months (each month individually and the 5-month average) for El Niño, La Niña, and for all conditions regardless of ENSO state.

Table 2
NUMBER OF CASES OF EACH REOF EXCEEDING POSITIVE/NEGATIVE THRESHOLD FOR EL NIÑO, LA NIÑA, AND ALL CASES, BY MONTH, 1947-48 THROUGH 1990-91

	Strong Positive REOF						Strong Negative REOF					
	N	D	J	F	M	All	N	D	J	F	M	All
REOF 1 (WPO)												
El Niño	0	0	0	0	1	1	2	3	1	2	3	11
La Niña	3	3	2	4	5	17	0	0	1	1	0	2
All	5	5	9	10	6	35	3	4	6	9	9	31
REOF 2 (PNA1)												
El Niño	1	2	2	0	2	7	3	1	4	5	3	16
La Niña	4	4	3	4	3	18	1	3	0	0	1	5
All	8	8	7	8	9	40	5	7	6	7	10	35
REOF 3 (PNA2)												
El Niño	2	1	2	0	1	6	2	3	3	4	2	14
La Niña	1	3	3	3	1	11	1	1	2	0	0	4
All	6	8	7	5	6	32	5	8	6	8	5	32
REOF 4												
El Niño	0	3	4	2	2	11	1	2	2	2	4	11
La Niña	1	0	2	0	2	5	1	2	1	2	1	7
All	6	8	7	5	7	33	5	9	6	8	9	37
REOF 5 (EP)												
El Niño	1	2	1	5	3	12	0	1	1	1	3	6
La Niña	2	1	1	1	1	6	2	3	2	4	1	12
All	5	9	7	11	8	40	4	7	5	8	6	30
REOF 6 (TNH)												
El Niño	2	4	1	2	3	12	3	2	2	4	3	14
La Niña	1	1	3	3	2	10	0	1	1	0	1	3
All	7	8	8	7	7	37	6	8	7	8	7	36
REOF 7												
El Niño	3	3	0	3	4	13	1	3	1	0	6	11
La Niña	2	2	2	0	3	9	4	2	0	1	3	10
All	10	13	6	5	10	44	8	10	6	5	10	39
REOF 8												
El Niño	0	2	2	1	0	5	1	2	1	2	3	9
La Niña	2	2	1	1	3	9	3	3	1	2	1	10
All	6	9	7	4	7	33	9	9	6	5	6	35

A χ^2 test on the contingencies in Table 2 and a *t*-test of the REOF amplitudes in Table 3 indicate that REOFs 1 and 2 are strongly differentiated according to the positive and negative phases of the SOI. Considering the sample set where all five months are pooled together, the two significance tests allow rejection of the null hypothesis that the REOFs are undifferentiated during El Niño *vs.* La Niña at greater than the 99% level of confidence. Three other REOFs (3, 5, 6) appear to differentiated, but not as strongly; for these cases, the null hypothesis may be rejected at a level of confidence ranging from 85% to more than 99%.

These five REOFs (1, 2, 3, 5, 6) are mapped on Figures 2-6, along with the precipitation anomaly pattern that occurs when a particular REOF is in its strong positive or strong negative extreme. Three other REOFs, which did not exhibit significant associations with ENSO, are not shown, but they represent circulations that also produce important precipitation anomalies. The values depicted by these REOF maps are correlations

Table 3
COMPOSITE OF REOFs FOR LA NIÑA AND EL NIÑO
BY MONTH AND FOR ALL MONTHS (NOVEMBER-MARCH), 1947-48 THROUGH 1990-91

	La Niña						El Niño					
	N	D	J	F	M	All	N	D	J	F	M	All
REOF 1 (WPO)												
n	11	11	11	11	11	11	12	12	12	12	12	12
Mean	0.70	0.44	0.19	0.41	0.79	0.51	−0.33	−0.72	−0.49	−0.54	−0.07	−0.43
Standard Deviation	1.09	0.91	1.17	0.89	0.93	0.46	0.83	0.75	0.82	0.78	0.84	0.43
REOF 2 (PNA1)												
n	11	11	11	11	11	11	12	12	12	12	12	12
Mean	0.46	0.13	0.68	0.61	0.38	0.45	−0.32	0.02	−0.31	−0.63	−0.28	−0.30
Standard Deviation	1.15	1.15	0.99	0.75	0.96	0.64	0.92	0.87	0.89	0.94	1.04	0.52
REOF 3 (PNA2)												
n	11	11	11	11	11	11	12	12	12	12	12	12
Mean	−0.18	0.22	0.25	0.49	0.05	0.17	−0.02	−0.22	−0.49	−0.54	−0.35	−0.33
Standard Deviation	0.68	0.93	1.15	0.97	0.75	0.49	0.99	0.95	1.22	1.10	1.04	0.72
REOF 4												
n	11	11	11	11	11	11	12	12	12	12	12	12
Mean	−0.19	−0.33	0.25	−0.16	0.16	−0.05	−0.11	0.15	0.31	−0.06	−0.20	0.02
Standard Deviation	0.83	0.78	0.90	0.59	1.04	0.42	0.69	1.03	1.22	0.87	1.30	0.72
REOF 5 (EP)												
n	11	11	11	11	11	11	12	12	12	12	12	12
Mean	−0.02	−0.39	−0.41	−0.41	−0.03	−0.25	0.11	0.06	0.14	0.24	−0.23	0.06
Standard Deviation	1.24	0.91	1.01	1.30	0.75	0.46	1.09	0.91	0.99	1.01	1.42	0.45
REOF 6 (TNH)												
n	11	11	11	11	11	11	12	12	12	12	12	12
Mean	0.01	−0.21	0.39	0.52	0.27	0.20	−0.13	0.18	−0.45	−0.12	−0.10	−0.12
Standard Deviation	0.70	0.67	1.22	0.71	0.88	0.29	1.28	1.06	0.99	1.29	1.15	0.80
REOF 7												
n	11	11	11	11	11	11	12	12	12	12	12	12
Mean	−0.42	−0.05	0.16	−0.14	−0.04	−0.10	0.11	−0.08	−0.17	0.22	−0.40	−0.06
Standard Deviation	1.47	0.89	0.71	0.70	1.01	0.53	0.90	0.90	0.55	1.00	1.39	0.53
REOF 8												
n	11	11	11	11	11	11	12	12	12	12	12	12
Mean	0.04	0.00	−0.04	−0.05	0.15	0.02	−0.01	0.14	0.24	−0.10	−0.29	0.00
Standard Deviation	1.48	1.17	0.70	1.06	1.06	0.86	0.68	1.02	1.06	1.00	1.11	0.66

between the REOF amplitude time series and the corresponding 700-mb height anomaly time series at each grid point. To identify these patterns, we follow Barnston and Livezey's (1987; denoted *BL*) classification of Northern Hemisphere anomalous circulation patterns.

The first REOF (14% of the variance) is the West Pacific Oscillation, with a north-south dipole of out-of-phase anomaly features. These anomalies are centered at about 55°N, just north of Kamchatka, and over a broader region at about 30°N, southeast of Japan. Tables 2 and 3 indicate the El Niño phase of ENSO favors the WPO phase with negative anomalies over Kamchatka and positive anomalies at lower latitudes of the western

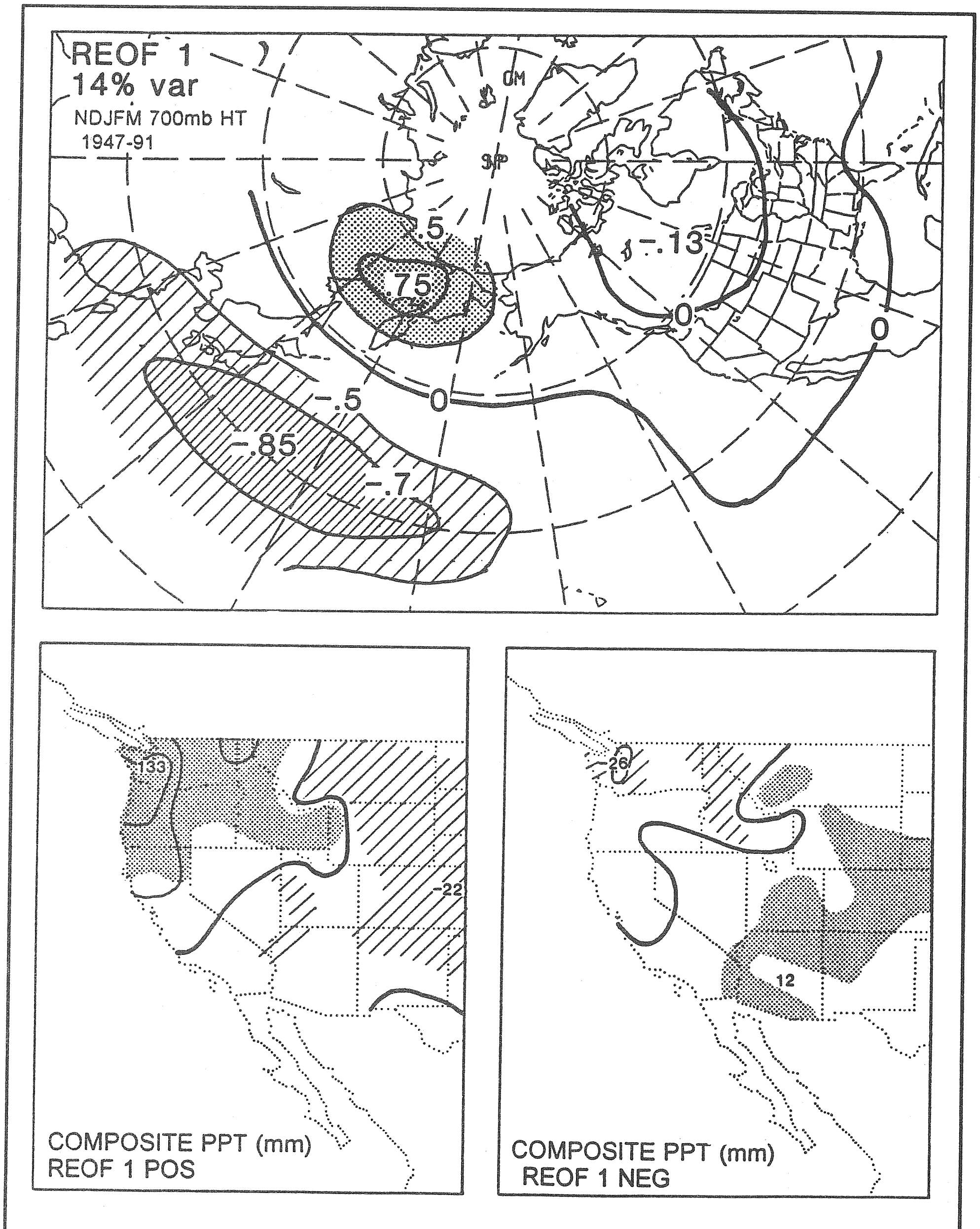

Figure 2. REOF 1 of Monthly NDJFM 700-mb Height Anomalies, 1947-48 through 1990-91, and Associated Precipitation Anomaly Patterns over the Western United States.
Precipitation anomalies are shown as composites of positive (left) and negative (right) extremes of each mode. REOF values are correlations, with shading on magnitudes exceeding 0.5. Shading (stippled/hatched) indicates (positive/negative) precipitation anomalies exceeding the 90% significance level, using a 2-tailed *t*-test. Amount of total anomaly variance accounted for is indicated for each mode.

North Pacific; the La Niña phase of ENSO favors the opposite — a blocking positive pressure anomaly over Kamchatka and an activated storm track to the south. The WPO link to ENSO was quite strong. During El Niño the WPO pattern was in its strengthened Kamchata Low state in 11 months and in its weakened Kamchatka Low state in only 2 months; during La Niña the WPO pattern was in its weakened Kamchata Low state in 17 months and in its strenghened Kamchatka Low state in only one month.

REOFs 2 and 3 (each accounts for about 11% of the variance) appear to be hybrids of the Pacific/North America pattern and are called PNA1 and PNA2 for the present study. REOF 2 is mainly a central North Pacific feature

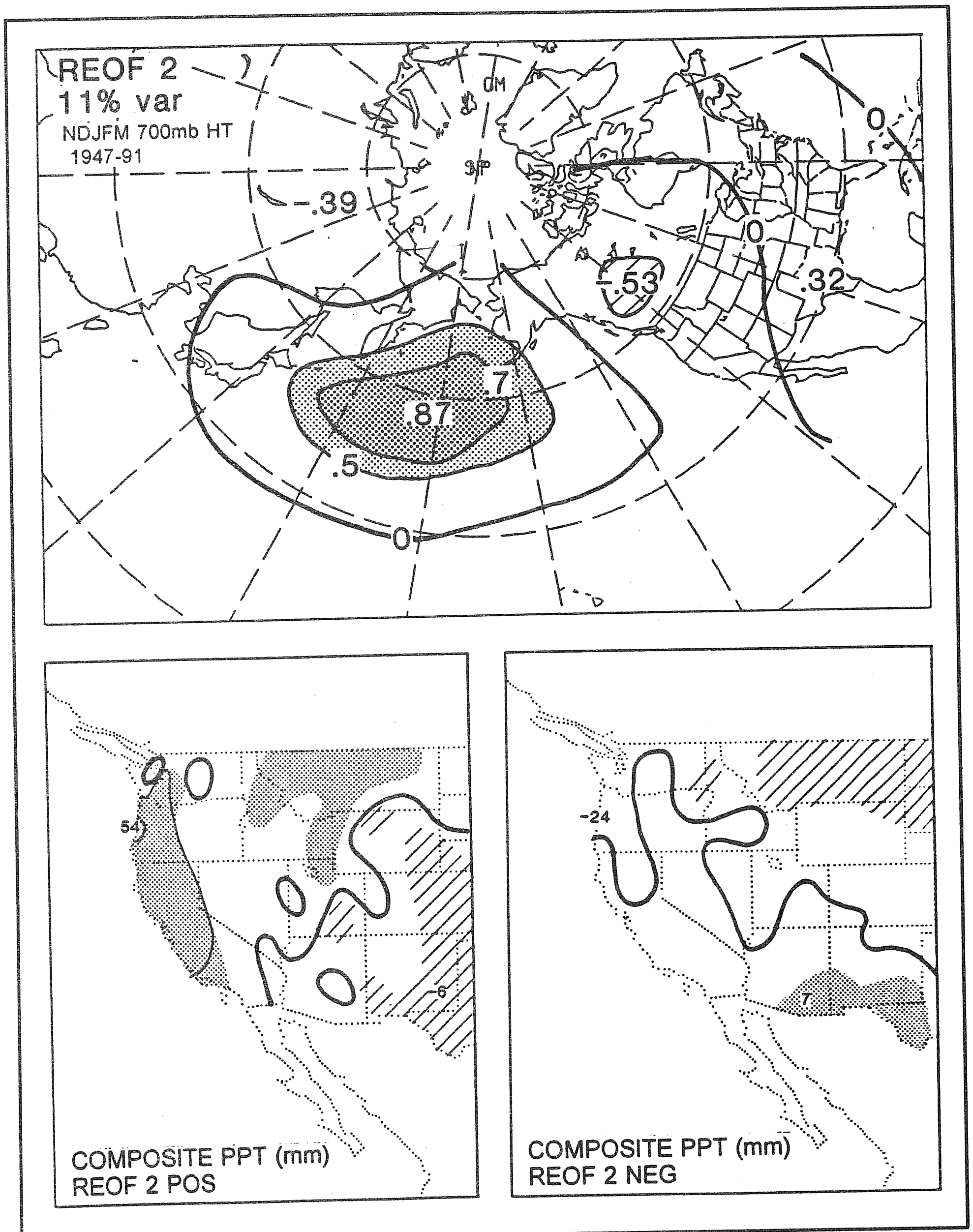

Figure 3. REOF 2 of Monthly NDJFM 700-mb Height Anomalies, 1947-48 through 1990-91, and Associated Precipitation Anomaly Patterns over the Western United States.
Precipitation anomalies are shown as composites of positive (left) and negative (right) extremes of each mode. REOF values are correlations, with shading on magnitudes exceeding 0.5. Shading (stippled/hatched) indicates (positive/negative) precipitation anomalies exceeding the 90% significance level, using a 2-tailed *t*-test. Amount of total anomaly variance accounted for is indicated for each mode.

centered at about 45°N 175°E but also contains a secondary center over western Canada at about 55°N 120°W. REOF 3 contains a modest center at about 50°N 150°W, in the western Gulf of Alaska; another center at about 60°N 90°W, over central Canada; and a strong, large center at about 30°N 80°W, over the southeastern United States. Hence, REOF 2 contains more of the central North Pacific portion of the PNA pattern, while REOF 3 contains more of the eastern extension of the PNA over North America. Tables 2 and 3 indicate the El Niño phase of ENSO favors the states of REOF 2 and 3 with deepened Aleutian or Gulf of Alaska Lows; in contrast, the La Niña phase of ENSO favors the circulation with

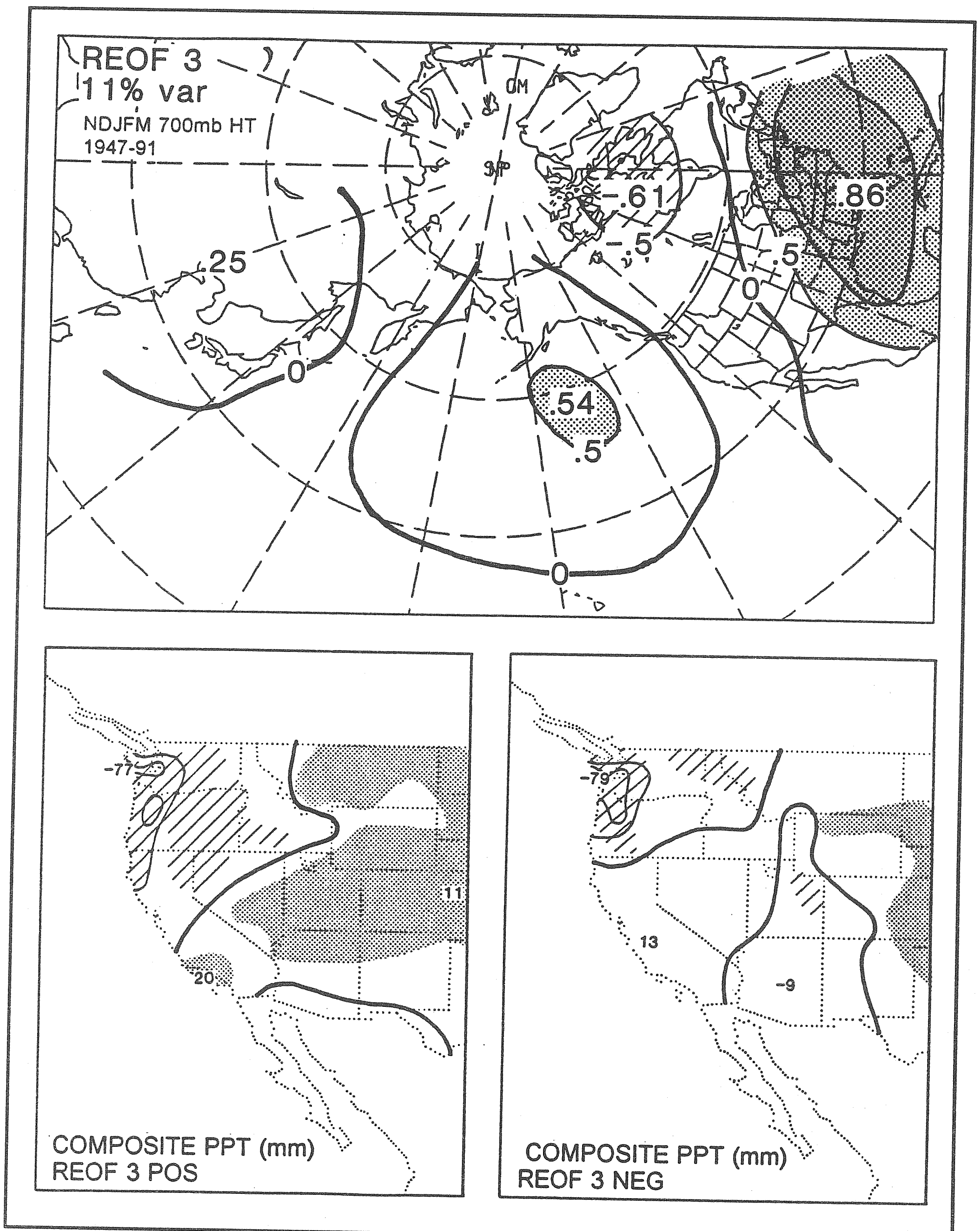

Figure 4. REOF 3 of Monthly NDJFM 700-mb Height Anomalies, 1947-48 through 1990-91, and Associated Precipitation Anomaly Patterns over the Western United States.
Precipitation anomalies are shown as composites of positive (left) and negative (right) extremes of each mode. REOF values are correlations, with shading on magnitudes exceeding 0.5. Shading (stippled/hatched) indicates (positive/negative) precipitation anomalies exceeding the 90% significance level, using a 2-tailed *t*-test. Amount of total anomaly variance accounted for is indicated for each mode.

positive anomalies south of the Aleutians or in the Gulf of Alaska, symptomatic of a less active storm track across the central North Pacific.

REOF 5 strongly resembles the Eastern Pacific (EP) pattern, with a dipole of out-of-phase north-south centers at about 60°N, over Alaska, and a broader center at about 30°N, north of the Hawaiian Islands. Tables 2 and 3 indicate the El Niño phase of ENSO favors the EP phase with positive anomalies over Alaska and negative anomalies to the south, over the eastern North Pacific; the La Niña phase of ENSO favors the opposite anomaly pattern, with negative anomalies to the north and positive

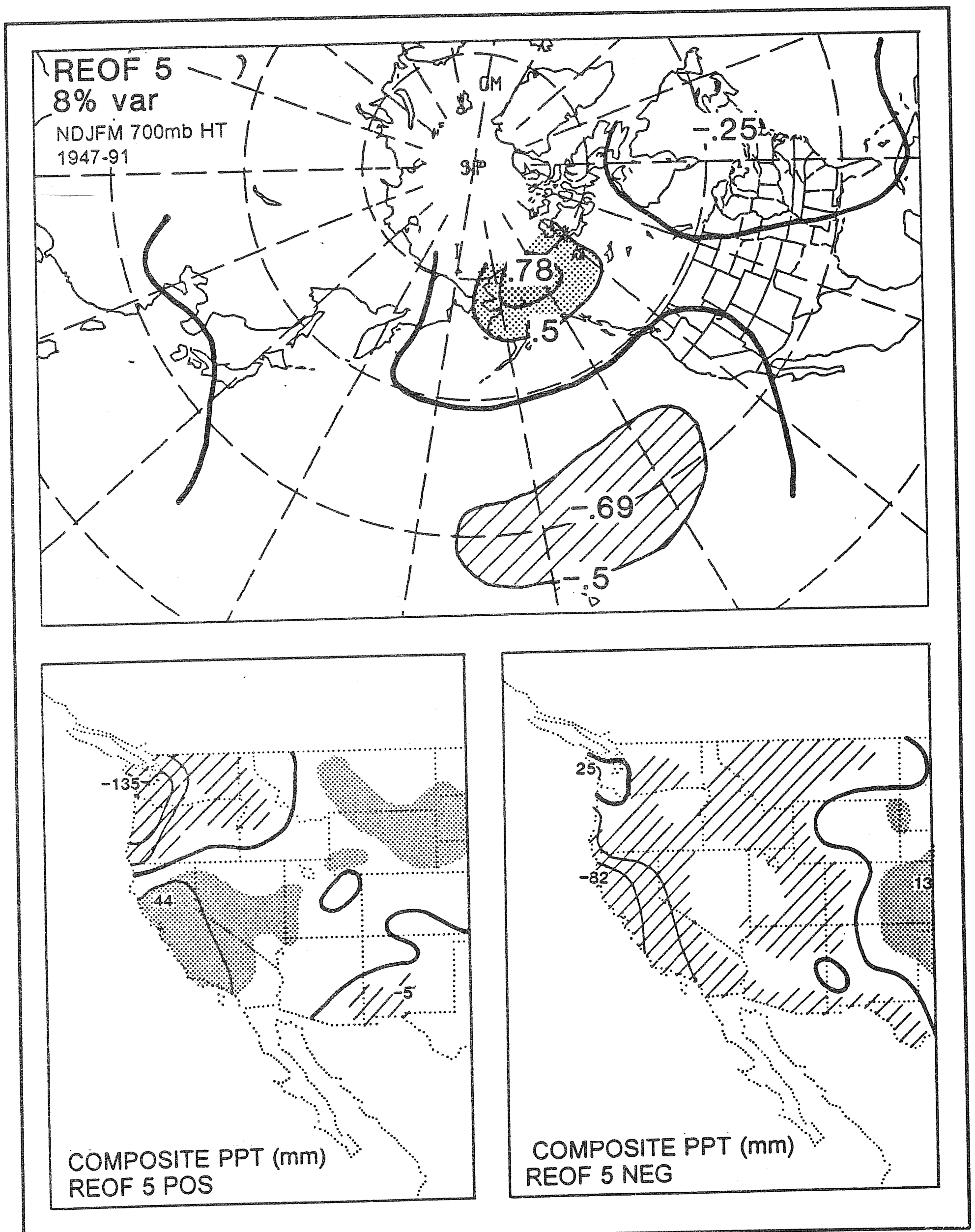

Figure 5. REOF 5 of Monthly NDJFM 700-mb Height Anomalies, 1947-48 through 1990-91, and Associated Precipitation Anomaly Patterns over the Western United States.
Precipitation anomalies are shown as composites of positive (left) and negative (right) extremes of each mode. REOF values are correlations, with shading on magnitudes exceeding 0.5. Shading (stippled/hatched) indicates (positive/negative) precipitation anomalies exceeding the 90% significance level, using a 2-tailed *t*-test. Amount of total anomaly variance accounted for is indicated for each mode.

anomalies to the south, symptomatic of a less active storm track across middle latitudes of the eastern North Pacific.

REOF 6 appears to be the Tropical/Northern Hemisphere pattern, with west-east out-of-phase centers at about 40°N 130°W, in the eastern North Pacific, and at 50°N 90°W, over Ontario, just north of the Great Lakes. Tables 2 and 3 indicate the El Niño phase of ENSO favors the TNH phase with negative anomalies off the west coast of the United States and positive anomalies upstream, over the Great Lakes. The La Niña state of ENSO is about equally split between both phases of TNH.

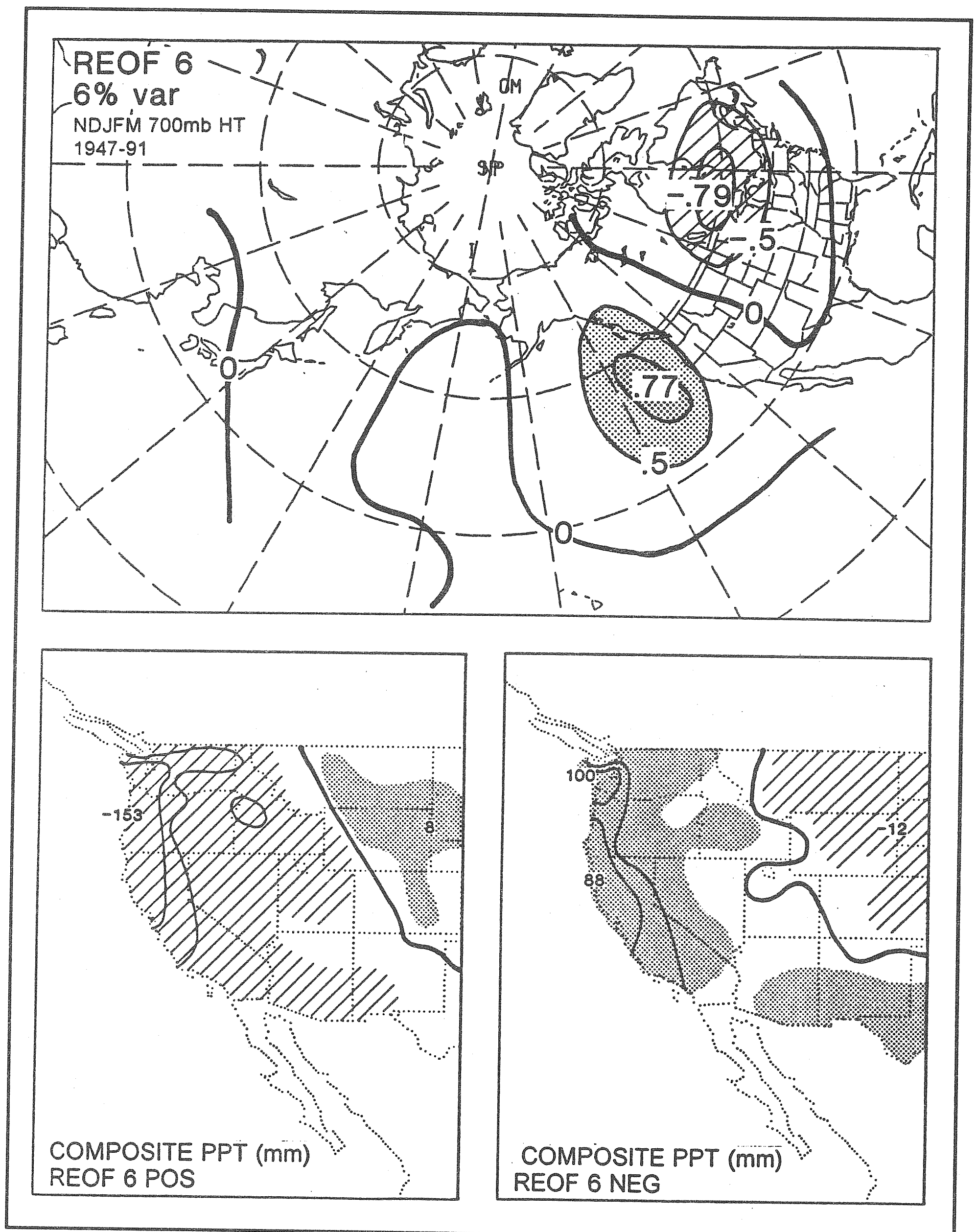

Figure 6. REOF 6 of Monthly NDJFM 700-mb Height Anomalies, 1947-48 through 1990-91, and Associated Precipitation Anomaly Patterns over the Western United States.
Precipitation anomalies are shown as composites of positive (left) and negative (right) extremes of each mode. REOF values are correlations, with shading on magnitudes exceeding 0.5. Shading (stippled/hatched) indicates (positive/negative) precipitation anomalies exceeding the 90% significance level, using a 2-tailed *t*-test. Amount of total anomaly variance accounted for is indicated for each mode.

Note that the present analysis differs from BL because this one included the more limited domain of the Pacific-North America half of the Northern Hemisphere, and because five months (NDJFM) were pooled in forming the EOFs and REOFs. BL performed separate analyses for each month, with the result that some of the modes exhibited considerable differences from one month to the next. Presumably these differ because of sampling variations (BL used the Northern Hemisphere 700-mb height archive from 1950 to 1984) and because the physical characteristics of the circulation change greatly over the annual cycle. On the latter, the BL PNA pattern (see BL, Figure 3, pp. 1092-1093) undergoes a dramatic expansion of its zonal wavelength from a minimum in September to a maximum in February, when zonal winds are maximum across the North Pacific, and then recedes to a minimum in April, when the westerlies have waned. The spatial configuration of REOF 2 more closely resembles the winter-month, longer-wavelength BL PNA pattern; REOF 3 is closer to the earlier-fall, later-spring, shorter-wavelength BL PNA patterns. This seasonal modulation of the PNA may be one reason the present NDJFM analysis has produced two PNA-like hybrids.

700-mb Height REOFs: Their Relationship to Precipitation Over the Western United States

To investigate the effect of the ENSO-related circulation patterns on precipitation, the distribution of precipitation over the western United States was examined during months with extreme patterns (positive or negative) of the five REOFs. Composites of precipitation anomalies were taken over NDJFM months with circulation patterns that project onto these REOFs with strongly positive and strongly negative amplitudes. Note that although this categorization was based exclusively on the amplitudes of the REOFs, the influence of tropical Pacific is implicit in the resulting relationships because these five REOFs are biased toward one of their extremes or the other (strong positive or strong negative) in association with the La Niña or El Niño state of the SOI. These composites are an average of positive anomalies over at least 30 months (the range was 30 to 44 months) in each of the extreme negative or extreme positive cases.

Several of the REOF-based precipitation composites have strong expressions over the western United States. Regarding REOF 1, the WPO, a relatively strong precipitation pattern appears over the western United States. The degree of this relationship is somewhat surprising in view of the western North Pacific location of its major centers. The positive anomaly over Kamchatka (blocking) phase of REOF 1 is wet over the Northwest from Northern California, Oregon, and Washington to Idaho, while parts of the Southwest through the central and northern Great Plains are dry. Several climate divisions in the Northwest exhibit composite precipitation anomalies exceeding 50 mm/month. Above-normal precipitation in the Northwest during positive REOF 1 months is consistent with the La Niña phase of ENSO tendency for wet conditions in this region, as the La Niña state favors this positive extreme of REOF 1

(Tables 2 and 3). The negative anomaly over the Kamchatka phase (strong, high-latitude westerlies in the western North Pacific) of REOF 1 has a precipitation pattern nearly opposite of that of the positive phase but not as strong. It is dry over the Northwest and wet from parts of the Southwest through the central Great Plains. This pattern is consistent with the tendency for negative REOF 1 to occur during the El Niño phase of ENSO, as indicated in Tables 2 and 3.

The weakened Aleutian Low phase of REOF 2 is associated with heavy precipitation over most of the West Coast and in the northern Rocky Mountain states; dry conditions appear in New Mexico, Texas, Colorado, and Wyoming. For the deep Aleutian Low phase of REOF 2, the precipitation pattern is nearly opposite, with a strip of positive precipitation anomalies in the Southwest and negative anomalies in the Northwest. Like REOF 1, these patterns are consistent with the precipitation tendencies for the La Niña and El Niño phases of ENSO, which favor positive and negative extremes of REOF 2, respectively.

The weakened Gulf of Alaska Low phase of REOF 3 is associated with lighter-than-normal precipitation over most of the Northwest and heavier-than-normal precipitation from the Southwest through the Great Plains. Surprisingly, the precipitation pattern for the strengthened Gulf of Alaska Low phase of REOF 3 is also light in the Pacific Northwest and rather weak over the rest of the region.

The phase of REOF 5 (the EP pattern) with positive 700-mb height anomalies over Alaska is associated with lighter-than-normal precipitation over the Northwest and heavier-than-normal precipitation over California and Nevada. This dry western pattern during a positive anomaly EP episode tends to occur during the El Niño phase of ENSO. The REOF 5 phase with negative 700-mb height anomalies over Alaska has lighter-than-normal precipitation over most of the western United States, but the largest anomalies are in central and northern California.

The phase of REOF 6 (the TNH pattern) with positive anomalies over the eastern North Pacific is associated with lighter-than-normal precipitation over the western United States, with strongest deficits over the coastal region from northern California to Washington. For the REOF 6 phase with negative anomalies over the eastern North Pacific, the precipitation pattern is nearly opposite, with heavier-than-normal precipitation over the western United States. This negative anomaly extreme of TNH is favored by the El Niño phase of ENSO.

Extreme Precipitation During Warm and Cool Phases of ENSO

The above analysis reveals the inclination toward a set of preferred modes of the monthly average circulation over the North Pacific-North America sector during the La Niña and El Niño states of the SOI. Along with this, there are distinct precipitation anomaly patterns over the western United

States. Despite the inclination toward anomalous regional precipitation of one sign or the other, the historical record shows that both extremes of precipitation do occur during La Niña and during El Niño. A follow-on issue, then, is whether the pattern of atmospheric circulation that produces precipitation and whether the associated geographic distribution of precipitation are changed from La Niña to El Niño, even though each may have anomalously heavy or light regional precipitation.

Thus, the second approach to examining the atmospheric circulation and precipitation behavior during ENSO extremes was to target particular regions, with conditioning on the state of ENSO and the state of precipitation. We examined two regions: the Pacific Northwest (PNW) and the Desert Southwest (DSW). Both of these exhibit El Niño and La Niña responses (*eg*, Redmond and Cayan 1994), with significant precipitation anomalies over the fall-winter-spring period following the La Niña or El Niño state of the SOI in JJASON. The PNW and DSW regions were prominent locales in the overall precipitation patterns associated with several of the REOF circulation anomalies discussed above.

Despite their long-term anomaly differences during the two extremes of ENSO, both positive and negative precipitation anomalies occur in individual months and seasons. To augment the analyses that have determined ENSO relationships to the amount of precipitation, this investigation attempts to determine how the causal atmospheric circulation and the associated spatial distribution of precipitation change in response to ENSO. (Hypothetically, it could be that for a given region all storms are identical, regardless of ENSO state, but that the storm frequency changes, so the total amount changes.) To examine this, composites were constructed of the 700-mb height anomaly during four groups: when ENSO is in its El Niño state and regional precipitation is either heavy or light, and when ENSO is in its La Niña state and regional precipitation is either heavy or light.

The extreme ENSO cases are based on the SOI values of the JJASON preceding the NDJFM months. Heavy/light precipitation is defined as a month when the magnitude of the regional precipitation anomaly exceeds 0.5 standard deviations. To test the consistency of the precipitation patterns, two periods were considered for each case: 1895-1930 and 1931-1991. This delineation was chosen because before 1931 divisional precipitation values were estimated from statewide averages, and after 1931 divisional values were constructed from stations within each division. No such long series is available for the 700-mb height, so only one map was constructed for its anomalies, using data from 1947 to present. The number of months used to form the average anomalies shown in the composites ranged from 5 to more than 30; in all but one case, 12 or more months were included.

Before describing precipitation patterns for each of the composites, some overall observations are pertinent. In general, the pair of precipitation maps (1895-1930 and 1931-1991) are quite consistent, with a surprising degree of agreement over the western United States sector. Downstream (east of about 100°W), the degree of correspondence is degraded, but we have not shown this area, because the intent is to study the western United States. This discussion does not describe the two individual maps for each case, but rather provides a view from the consensus of major features of each.

Extreme Precipitation Patterns in the PNW Region

The first set of circulation and precipitation composites is for the PNW. SOI negative (Figure 7) and positive (Figure 8) are divided into the PNW wet (left) and the PNW dry (right) cases. The SOI negative wet case has heavy precipitation extending from northern California through the Pacific Northwest. Monthly anomalies in the PNW region exceed 100 mm. The 700-mb height anomaly pattern features a broad, negative anomaly centered at about 45°N 160°W and extending from the Aleutian Islands to the North American coast. To the south are strong positive anomalies throughout most of the subtropical North Pacific, and downstream there is a negative anomaly center over the southeastern United States. This pattern is a symptom of active storms tracking zonally across from the

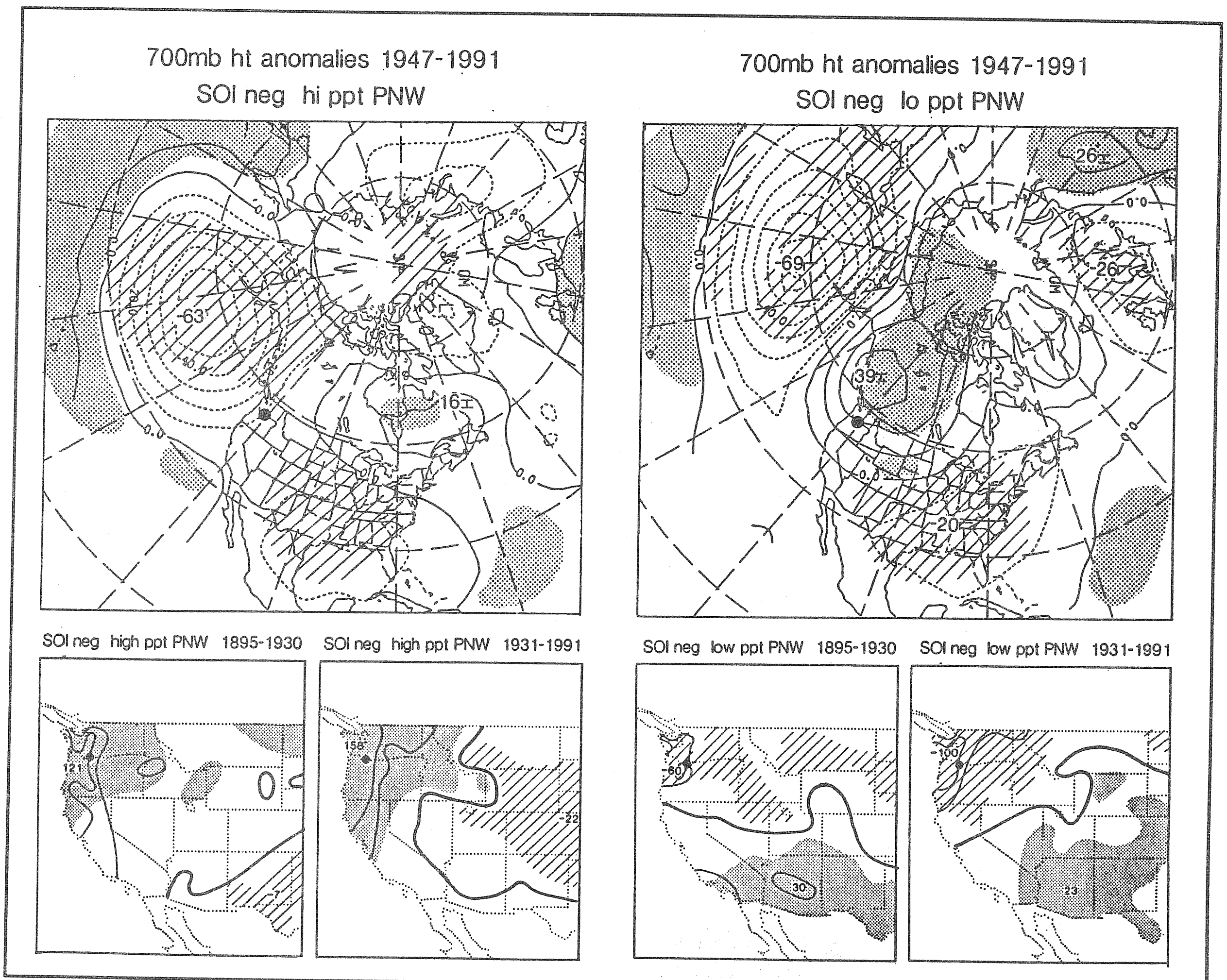

Figure 7. Composite 700-mb Height Anomaly Pattern and Precipitation Distribution over the Western United States for Negative SOI — Pacific Northwest.

Classes are divided into months when PNW region (indicated by dot; but see Figure 1) was wet (left) and dry (right). Anomalies exceeding the 90% significance level, using a 2-tailed t-test, are shaded (stippled/hatched, designating wet/dry). 700-mb height anomalies contoured at 10-m intervals, precipitation anomalies contoured at 0, 25, and 50 mm.

central North Pacific into the Pacific Northwest. The SOI negative dry case has light precipitation throughout the Northwest, with maximum negative anomaly values in excess of 75 mm. To the south, there is heavy precipitation over the Southwest. The 700-mb height anomaly pattern is quite similar to that for the SOI negative wet PNW case, but the North Pacific negative anomaly center is stationed farther west at about 170°W, and there is a strong positive anomaly seated over western Canada. With the strong positive anomalies over the subtropical North Pacific and the negative anomalies over the southeastern United States, this is strong expression of the PNA pattern (Barnston and Livezey 1987).

In contrast to the atmospheric circulations that prevail during the negative SOI precipitation patterns, those for the positive SOI (Figure 8) do not have very strong anomalies over the North Pacific, and largest anomaly centers are more constricted to higher latitudes. The SOI positive wet PNW composite has heavy precipitation extending from Oregon and Washington through Idaho. To the south, precipitation is light over the southwestern United States, consistent with the positive 700-mb height

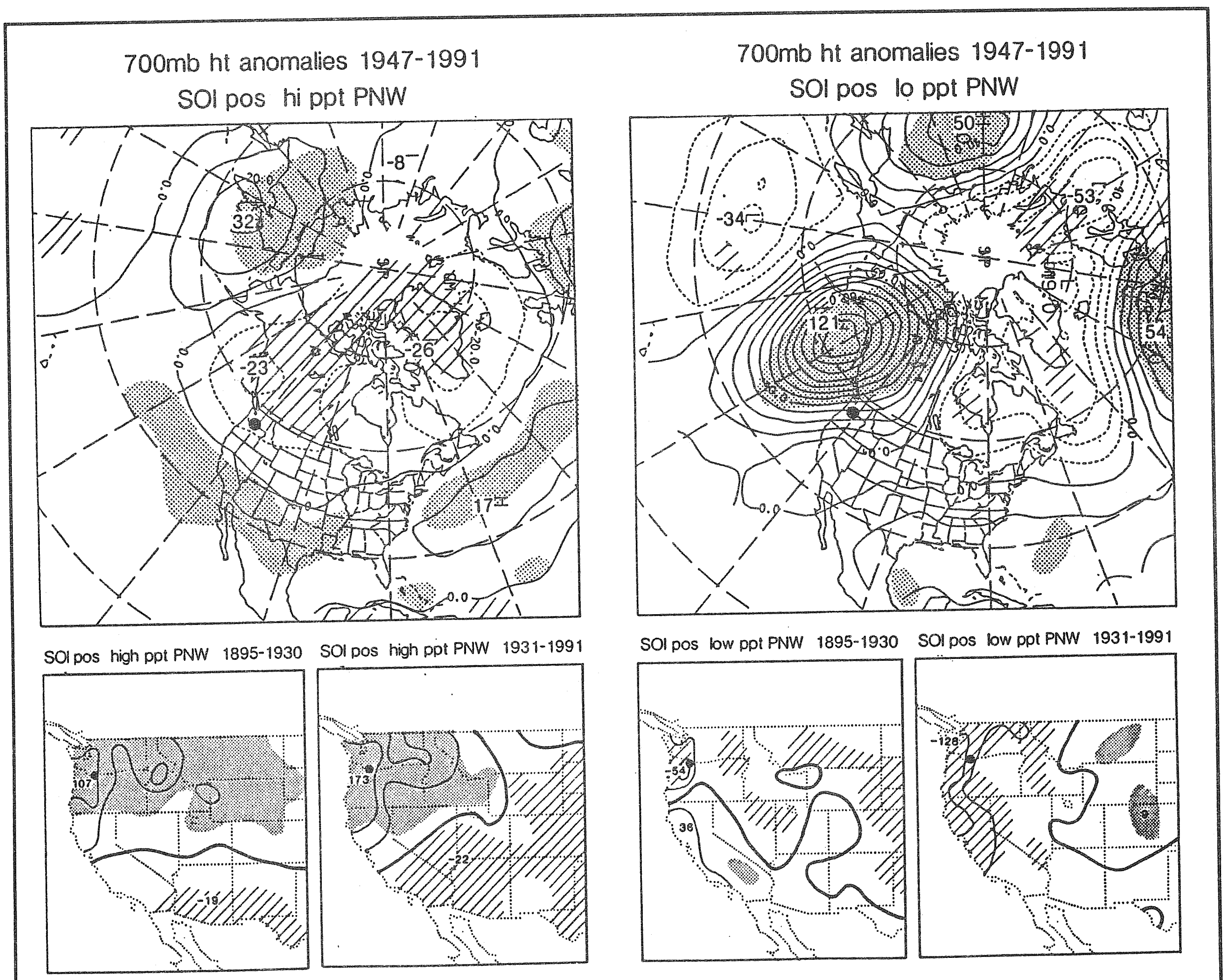

Figure 8. Composite 700-mb Height Anomaly Pattern and Precipitation Distribution over the Western United States for Positive SOI — Pacific Northwest.
Classes are divided into months when PNW region (indicated by dot; but see Figure 1) was wet (left) and dry (right). Anomalies exceeding the 90% significance level, using a 2-tailed t-test, are shaded (stippled/hatched, designating wet/dry). 700-mb height anomalies contoured at 10-m intervals, precipitation anomalies contoured at 0, 25, and 50 mm.

anomalies overlying this region. The SOI positive dry PNW pattern is dry over much of the western United States, although somewhat patchy. The 700-mb height anomaly pattern has a strong positive anomaly straddling the Gulf of Alaska and the Alaska/British Columbia region. This pattern lacks a strong teleconnection to the west, indicating the behavior over the central and western North Pacific during SOI positive dry PNW months is not very similar from one event to the next.

Extreme Precipitation Patterns in the DSW Region

The second set of circulation and precipitation composites is for the DSW precipitation extremes during SOI negative (Figure 9) and positive (Figure 10). Wet and dry cases are mapped on the left and right panels, respectively. The SOI negative wet DSW case has heavy precipitation extending from California through New Mexico and northward to the central Rocky Mountain states. Precipitation is light over the Northwest, showing a north-south out-of-phase pattern similar to some of those seen in Figures 7 and 8 associated with the PNW wet/dry composites. The

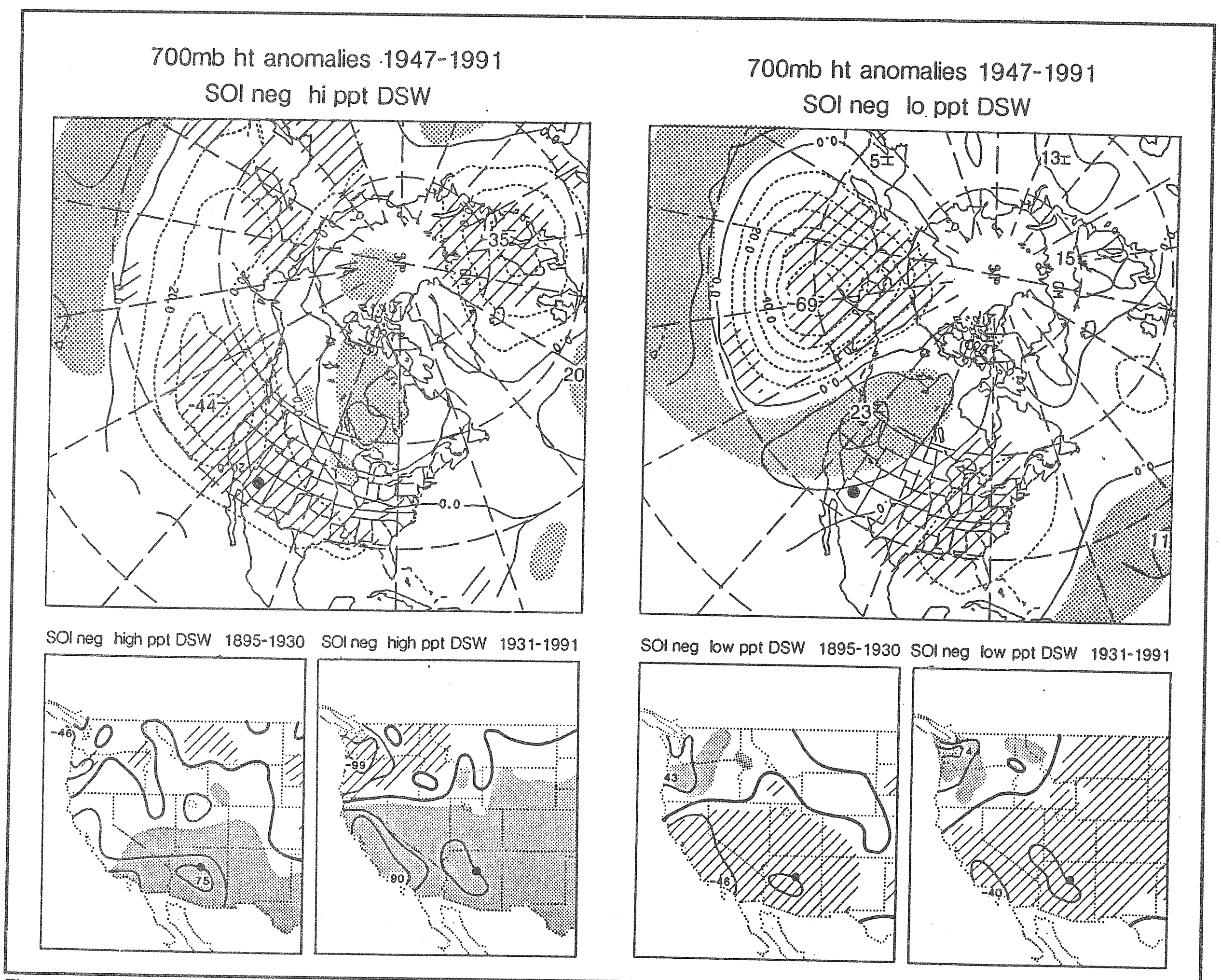

Figure 9. Composite 700-mb Height Anomaly Pattern and Precipitation Distribution over the Western United States for Negative SOI — Desert Southwest.

Classes are divided into months when DSW region (indicated by dot; but see Figure 1) was wet (left) and dry (right). Anomalies exceeding the 90% significance level, using a 2-tailed *t*-test, are shaded (stippled/hatched, designating wet/dry). 700-mb height anomalies contoured at 10-m intervals, precipitation anomalies contoured at 0, 25, and 50 mm.

700-mb height anomalies feature negative anomalies in low-middle latitudes (about 30-40°N) from 150°W across the entire western half of the United States. This zonal swath is consistent with active storms and broad heavy precipitation across the southern United States shown by the precipitation maps. Like the SOI negative PNW patterns, there are positive anomalies across the subtropical western North Pacific. The SOI negative dry DSW composite is nearly opposite from the SOI negative wet DSW case, with light precipitation extending from California through New Mexico and northward to the Rocky Mountain states. Also, precipitation is out of phase in the Pacific Northwest, with patches of heavy precipitation there. The SOI negative dry DSW 700-mb anomaly pattern is similar to the one for SOI negative dry PNW, with a strong negative anomaly south of the Aleutian Islands. However, the positive anomaly enveloping the West Coast for the dry DSW case is extended farther south than that of the PNW case, and actually joins the positive anomalies that cover the subtropical North Pacific. With the negative anomaly center stationed downstream over the southeastern United States, this is another strong example of the PNA pattern.

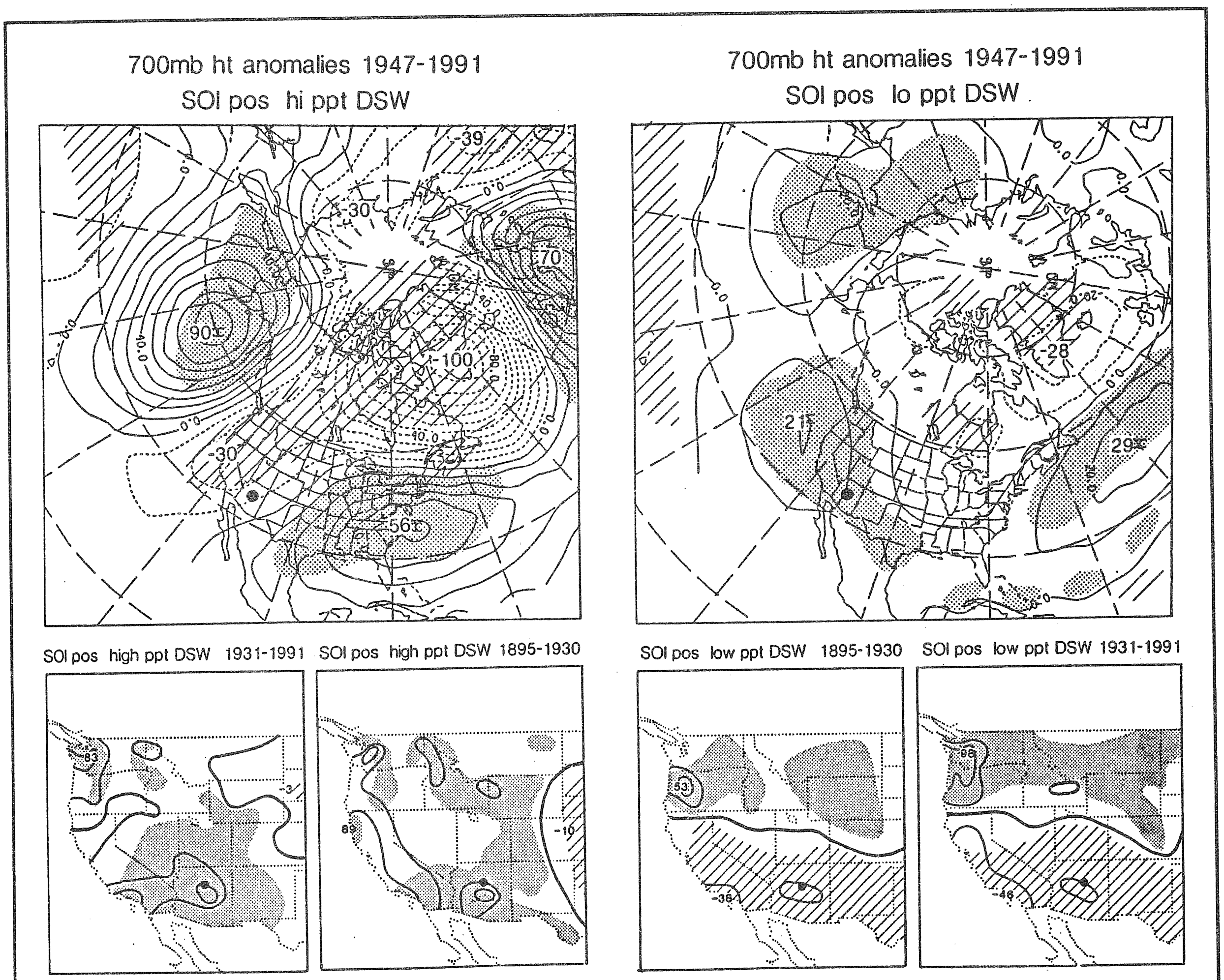

Figure 10.Composite 700-mb Height Anomaly Pattern and Precipitation Distribution over the Western United States for Positive SOI — Desert Southwest.

Classes are divided into months when DSW region (indicated by dot; but see Figure 1) was wet (left) and dry (right). Anomalies exceeding the 90% significance level, using a 2-tailed *t*-test, are shaded (stippled/hatched, designating wet/dry). 700-mb height anomalies contoured at 10-m intervals, precipitation anomalies contoured at 0, 25, and 50 mm.

As in the PNW composites, the positive SOI patterns for DSW wet and dry cases (Figure 10) are very different from their negative SOI counterparts. The SOI positive wet DSW composite has heavy precipitation covering much of the western United States, including most of the Southwest and parts of the Rocky Mountains and the Northwest. In contrast to the extensive zonally-oriented pattern of the SOI negative wet DSW case, the SOI positive wet DSW circulation is a tight, high amplitude wave pattern with positive 700-mb height anomalies to the west centered at about 50°N 150°W, negative anomalies over the West Coast, and positive anomalies downstream over the southeastern United States. The negative anomalies over the West Coast are actually a southward-extending tongue of a circumpolar patch that also covers most of Canada, the Arctic, and the far North Atlantic. (Note that the SOI negative wet DSW case had positive 700-mb height anomalies over much of this region.) Finally, the SOI positive dry DSW composite has light precipitation over a band from California to Texas. A marked feature of the precipitation pattern is the out-of-phase heavy precipitation over the Northwest from Oregon and Washington to Wyoming and Montana. The circulation is again very distinct from that of the negative SOI counterpart, with positive 700-mb height anomalies over the eastern North Pacific just off the West Coast through the DSW region. Interestingly, these are associated with negative anomalies in the subtropics of the western North Pacific.

Summary and Conclusions

Two approaches were taken to decipher the response to the El Niño/ Southern Oscillation by atmospheric circulation over the North Pacific/ North America and by precipitation over the western conterminous United States.

First, using rotated empirical orthogonal functions of the 700-mb height, prominent monthly anomalous atmospheric circulation patterns were identified over the November-March cool "season" from a data set covering 1947 to 1991. By compositing the amplitudes of each REOF, those REOFs that are significantly related to positive and negative phases of the SOI were determined.

Second, an analysis was conducted based on extreme regional western United States precipitation during each of the two ENSO states. Precipitation averaged over the Pacific Northwest and the Desert Southwest was targeted. This second part was aimed at:

- Determining differences in the atmospheric circulation responsible for the precipation anomalies between the two ENSO states, and
- Determining the extent and configuration of the spatial precipitation anomalies associated with the PNW and DSW regional extremes and how they vary from the El Niño to the La Niña states.

Concerning the response of individual circulaton modes to ENSO, five modes exhibited preferences of either their positive or negative extremes during the NDJFM cool season that overlaps with a JJASON whose average normalized SOI anomaly magnitude exceeded 0.5. The REOFs were associated with the patterns determined by Barnston and Livezey (1987) in their study of the anomalous monthly atmospheric circulation over the Northern Hemisphere. Four of the five — identified as the Western Pacific Oscillation, two hybrids of the Pacific/North American pattern, and the East Pacific pattern —had a symmetric response, with opposite biases for the El Niño and La Niña phases of ENSO. The fifth mode, the Tropical/Northern Hemisphere pattern, exhibited biases during El Niño episodes but not during La Niña. Virtually all of the five REOFs have significant anomaly expressions over the North Pacific sector. Some contained extremely strong ENSO relationships. For example, during El Niño the WPO pattern was in its strengthened Kamchata Low state in 11 months and in its weakened Kamchatka Low state in only 2 months. In contrast, during La Niña the WPO pattern was in its weakened Kamchata Low state in 17 months and in its strenghened Kamchatka Low state in only 1 month. Using composites, it is clear that most of these modes produce statistically significant, regional-scale precipitation anomaly patterns over the western United States. Even the WPO, with its western-centered anomaly features, has a strong precipitation anomaly association over the western United States. During El Niño, these modes tend to reinforce the tendency for the northwestern United States to be dry and the southwestern United States to be wet during El Niño, and for the opposite conditions to occur during La Niña.

From the analyses based on the PNW and DSW regional precipitation, it was determined that precipitation anomalies cover broad regional scales, but with quite different geographic distributions during El Niño *vs.* La Niña. In turn, these precipitation distributions and their differences are driven by the large-scale atmospheric circulation, which differs greatly during El Niño *vs.* La Niña . Consistent with results of the analysis of the NDJFM circulation modes in the first part of this study, the El Niño circulation patterns tended to have strong negative 700-mb height anomalies and attendant strengthened westerly winds over middle latitudes of the central-to-eastern North Pacific sector. In the subtropics west of the international date line, the height anomalies were positive during El Niño, both for heavy and light regional precipitation. In cases where the westerlies break through to the West Coast, precipitation is heavy, but in cases where the westerlies are confined to the central North Pacific with a ridge of high pressure to their east (over the West Coast), precipitation is light.

Both positive and negative precipitation anomalies arising during La Niña cases were quite different from those during El Niño. The La Niña circulation patterns tended to have a weak anomaly structure over much of the North Pacific, with strongest anomaly centers over high latitudes and over the North American sector. The La Niña circulation patterns associated with regional precipitaton anomalies featured rather strong meridional flow anomalies, as opposed to those for El Niño, which displayed zonal flow anomalies.

Concerning the geographic distribution of precipitation anomalies associated with PNW and DSW conditions, there were broad regional scales of precipitation anomalies. Consistent with the differences between the atmospheric circulations of the two ENSO states, the geographic distribution of precipiation differed from El Niño to La Niña. The reliability of this result was indicated by the consistency of the patterns derived for each subset from two separate periods: 1895-1930 and 1931-1991.

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